

Searching for warm/hot intergalactic medium with DIOS (Diffuse Intergalactic Oxygen Surveyor)

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Recent Activities in Observational Cosmology Group, University of Tokyo (1)

- **SDSS galaxy and quasar statistics**
 - topological analysis of galaxy distribution (Hikage et al. 2003, 2004; Park et al. 2005)
 - phase correlation statistics of SDSS galaxies (Hikage et al. 2005)
 - 3pt correlation functions of SDSS galaxies (Kayo et al. 2004)
 - widest-separation lensed quasar from SDSS (Inada et al. 2003; Oguri et al. 2004)
 - 2pt correlation functions of SDSS quasars and dark energy (Yahata et al. 2005)
 - constraints on the deviation from Newton's law of gravity from SDSS galaxy power spectrum (Shirata, Shiromizu, Yoshida & Suto 2005)
 - testing the Galactic dust map against SDSS galaxy number counts (Yahata et al. in preparation)

Recent Activities in Observational Cosmology Group, University of Tokyo (2)

- **Dark halo and galaxy cluster**
 - triaxial modeling of dark matter halos (Jing & Suto 2002; Oguri, Lee & Suto 2003; Lee, Jing & Suto 2005)
 - highest-angular resolution SZ maps in submm and mm (Komatsu et al. 1999, 2001; Kitayama et al. 2004)
- **Spectroscopy of a transiting extrasolar planet**
 - constraints on planetary atmosphere (Winn et al. 2004; Narita et al. 2005)
 - first detection of the spin-orbit misalignment in an extrasolar planetary system with the Rossiter effect (Ohta, Taruya & Suto 2005; Winn et al. 2005)
- **Search for dark baryon with DIOS**
 - a proposal of oxygen emission line search (Yoshikawa et al. 2003, 2004)
 - feasibility of an absorption line search with XEUS along a GRB afterglow (Kawahara et al. 2005)

Cosmic energy budget



baryons

■ ordinary matter makes up merely 4 percent

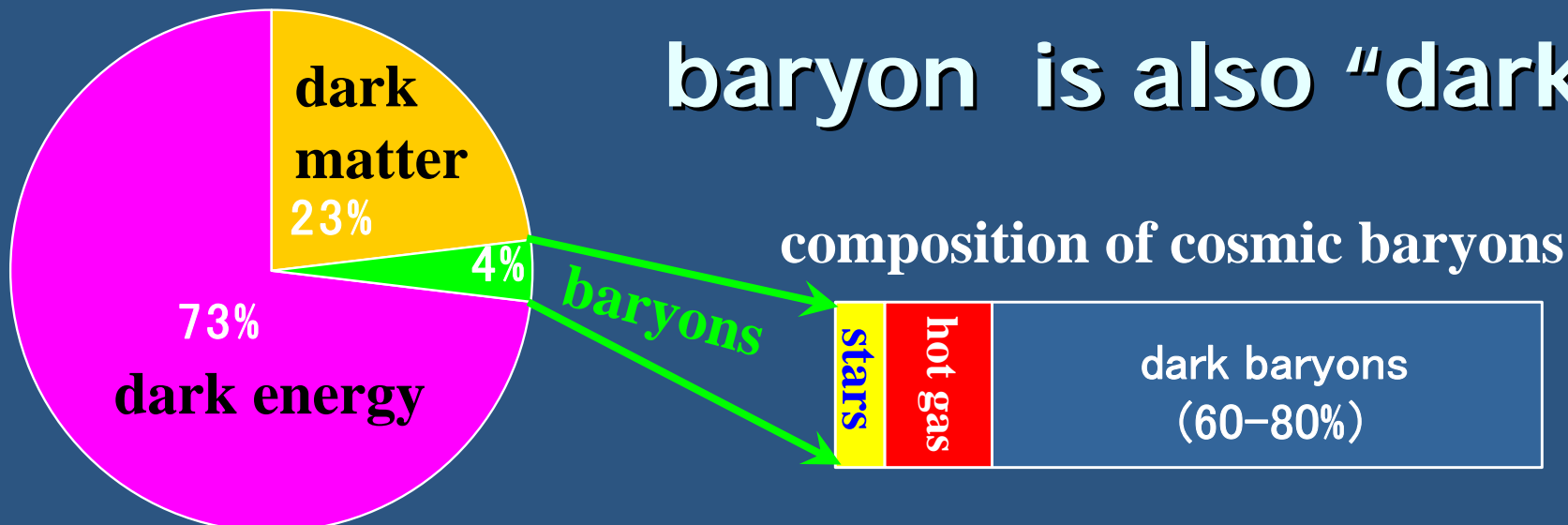
dark matter

■ galaxies and clusters are surrounded by invisible mass an order-of-magnitude more massive than their visible part

dark energy

- dominated by even more exotic component !
- homogeneously fills the universe (unclustered)
- repulsive force (negative pressure; $P = -\rho$)
- Einstein's cosmological constant ?

More intriguingly, most of the cosmic baryon is also "dark"



Component	Central	Maximum	Minimum	Grade ^a
Cosmic Baryon Budget: Fukugita, Hogan & Peebles: ApJ 503 (1998) 518				
1. Stars in spheroids	0.0026 h_{70}^{-1}	0.0043 h_{70}^{-1}	0.0014 h_{70}^{-1}	A
2. Stars in disks	0.00086 h_{70}^{-1}	0.00129 h_{70}^{-1}	0.00051 h_{70}^{-1}	A-
3. Stars in irregulars	0.000069 h_{70}^{-1}	0.000116 h_{70}^{-1}	0.000033 h_{70}^{-1}	B
4. Neutral atomic gas	0.00033 h_{70}^{-1}	0.00041 h_{70}^{-1}	0.00025 h_{70}^{-1}	A
5. Molecular gas	0.00030 h_{70}^{-1}	0.00037 h_{70}^{-1}	0.00023 h_{70}^{-1}	A-
6. Plasma in clusters	0.0026 $h_{70}^{-1.5}$	0.0044 $h_{70}^{-1.5}$	0.0014 $h_{70}^{-1.5}$	A
7a. Warm plasma in groups	0.0056 $h_{70}^{-1.5}$	0.0115 $h_{70}^{-1.5}$	0.0029 $h_{70}^{-1.5}$	B
7b. Cool plasma	0.002 h_{70}^{-1}	0.003 h_{70}^{-1}	0.0007 h_{70}^{-1}	C
7'. Plasma in groups	0.014 h_{70}^{-1}	0.030 h_{70}^{-1}	0.0072 h_{70}^{-1}	B
8. Sum (at $h = 70$ and $z \simeq 0$).....	0.021	0.041	0.007	...

Can we understand the dark sides of the universe in foreseeable future ?

■ Dark matter

- maybe new results from on-going accelerators in next 5-10 years, but not from astronomy

■ Dark energy

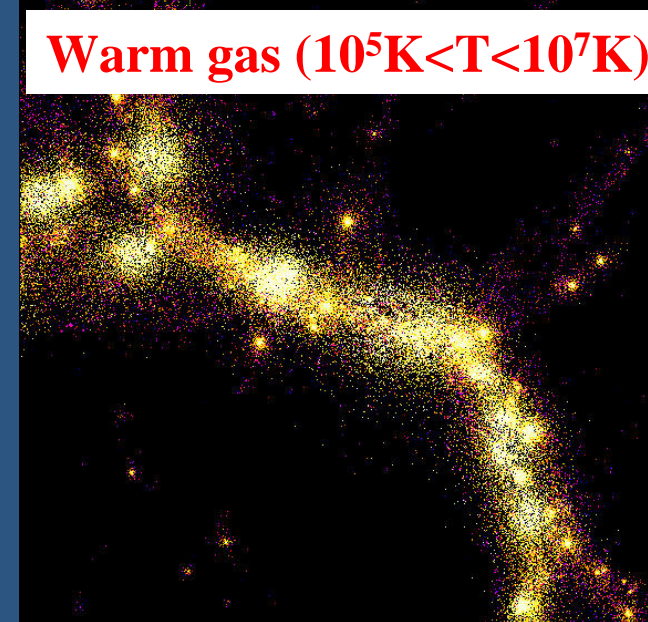
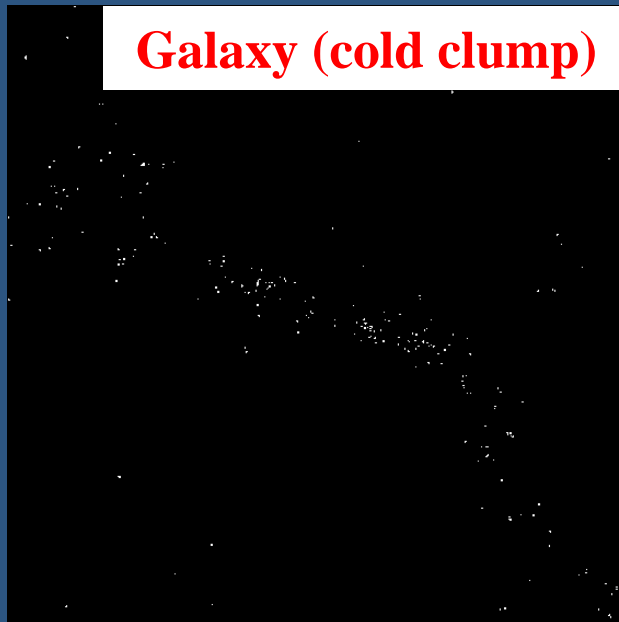
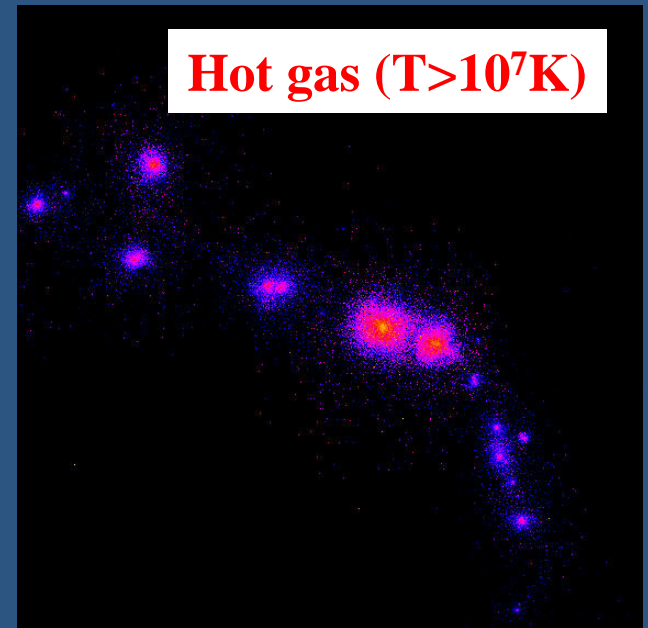
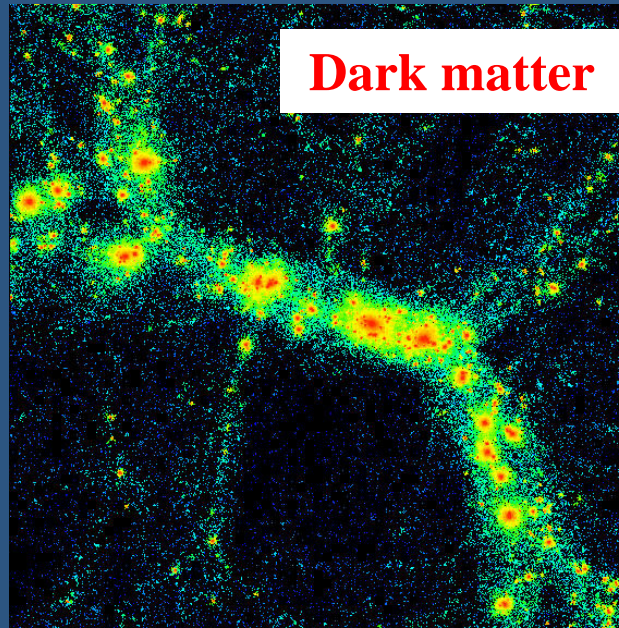
- unlikely to have any breakthroughs from future experiments and/or theories in high energy in this century
- astronomy may be still very useful

■ Dark baryons

- only astronomical observations can make a scientific new contribution since high-energy physicists know baryons too well !

Simulated distribution of matter in the universe

$(30h^{-1}\text{Mpc})^3$
box around a
massive
cluster at
 $z=0$



Λ CDM SPH
simulation
(Yoshikawa,
Taruya, Jing &
Suto 2001)

Four phases of cosmic baryons

Dave et al. *ApJ* 552(2001) 473

- Condensed: $\delta > 1000, T < 10^5 \text{K}$
 - Stars + cold intergalactic gas
- Diffuse: $\delta < 1000, T < 10^5 \text{K}$
 - Photo-ionized intergalactic medium
 - Ly α absorption line systems
- Hot: $T > 10^7 \text{K}$
 - X-ray emitting hot intra-cluster gas
- Warm-hot: $10^5 \text{K} < T < 10^7 \text{K}$
 - Warm-hot intergalactic medium (*WHIM*)

Three complementary methods to search for dark baryons

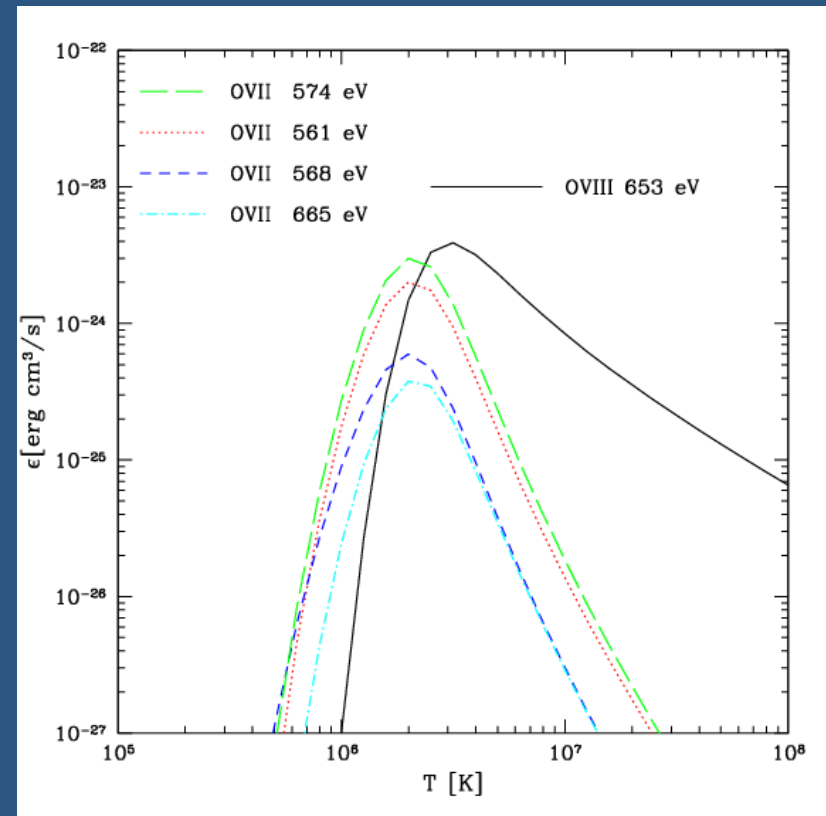
- absorption line systems of OVI, OVII and OVIII along background QSOs in UV and soft X-ray
 - several detections reported with FUSE, Chandra, and XMM/Newton (e.g., Fang et al. 2002, Fujimoto et al. 2004, Nicastro et al. 2005)
- emission line survey (mainly of OVII and OVIII)
 - goal of DIOS (Yoshikawa et al. 2003, 2004)
- absorption line systems along a GRB afterglow in soft X-ray
 - feasible with XEUS (X-ray Evolving Universe Spectroscopy) (Fiore et al. 2000, Kawahara et al. 2005)

Emission lines of oxygen in WHIM

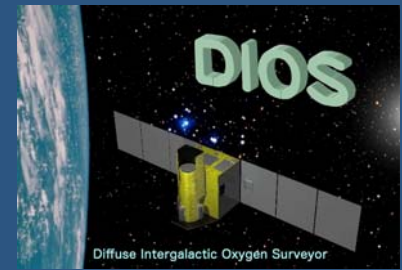
OvII (561eV, 568eV, 574eV, 665eV) , OvIII (653eV)

- **Why oxygen emission lines ?**
 - Most abundant other than H and He
 - Good tracers of gas around $T=10^6 \sim 10^7$ K
 - No other prominent lines in $E=500-660\text{eV}$
 - Not restricted to regions towards background QSOs

⇒ *systematic WHIM survey*



Requirements for detection

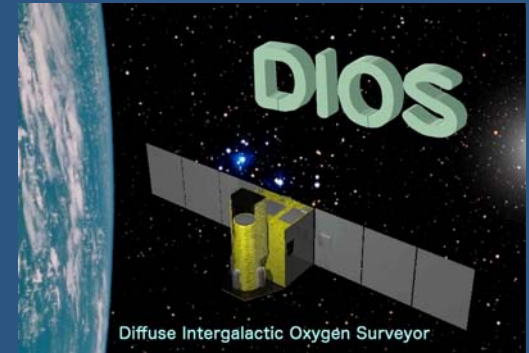


- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
 - $\Delta E < 5\text{eV} \Rightarrow$ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
 - $S_{\text{eff}} = 100\text{cm}^2, \Omega = 1\text{deg}^2 \Rightarrow$ 4-stage reflection telescope
- Angular resolution is not so important (but useful in removing point source contaminations)

$$\theta \approx 1^\circ \left(\frac{600 h^{-1} \text{Mpc}}{D} \right) \left(\frac{L}{10 h^{-1} \text{Mpc}} \right)$$

DIOS: Diffuse Intergalactic Oxygen Surveyor

A Japanese proposal of a dedicated X-ray mission to search for dark baryons



- **PI: Takaya Ohashi** (Tokyo Metropolitan Univ.)
 - + Univ. of Tokyo, JAXA/ISAS, Nagoya Univ., Tokyo Metro. Univ.
- A dedicated small satellite with cost < 40M USD
- Proposed launch in **2008~2010** (not yet approved; looking for international collaboration)
- Unprecedented energy spectral resolution: **$\Delta E=2\text{eV}$ in soft X-ray band (0.3-1.5keV)**
- Aim at unambiguous detection of WHIM via **Oxygen emission lines**
- Estimate the dark baryon (WHIM) density contribution to the total cosmic baryon budget

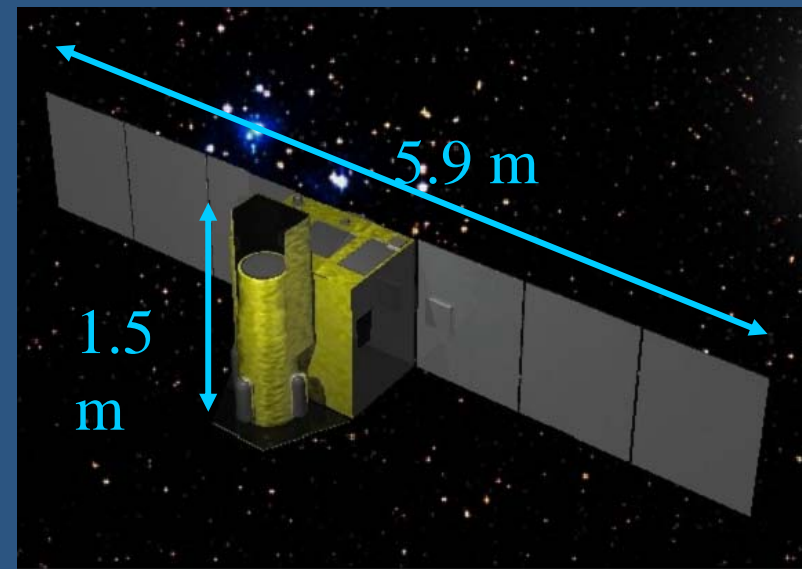
DIOS: instrument and spacecraft

Area	$> 100 \text{ cm}^2$
Field of View	50' diameter
$S\Omega$	$\sim 100 \text{ cm}^2\text{deg}^2$
Angular Resol.	3' (16^2 pixels)
Energy Resol.	2 eV (FWHM)
Energy Range	0.3 – 1.5 keV
Life	$> 5 \text{ yr}$

Altitude: $\sim 550 \text{ km}$

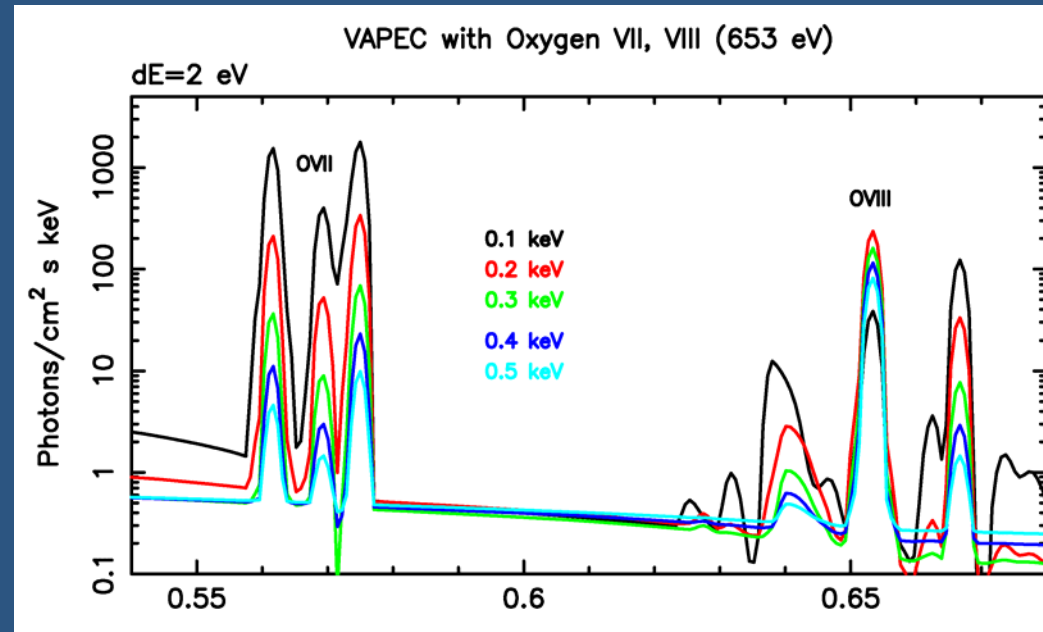
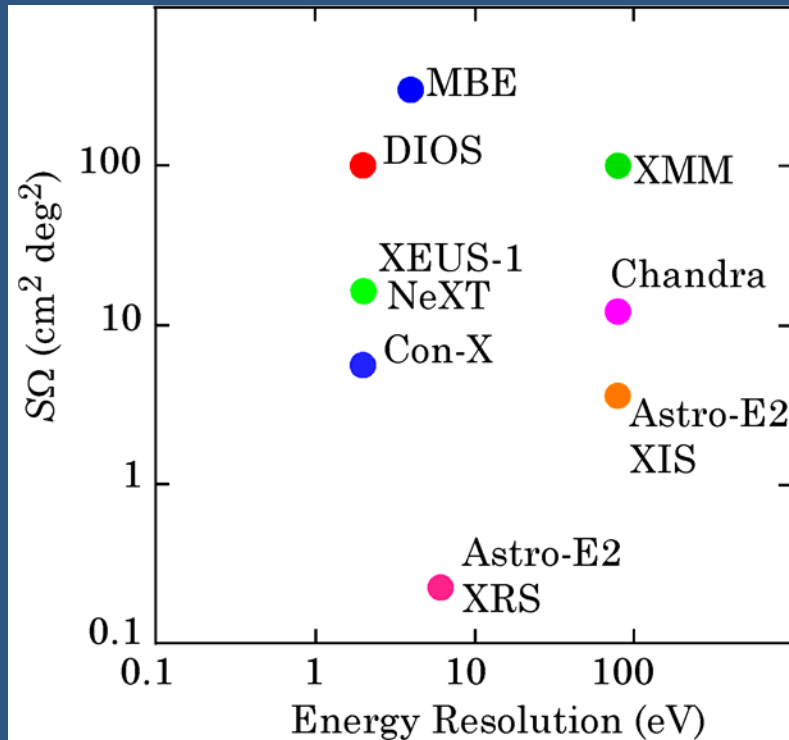
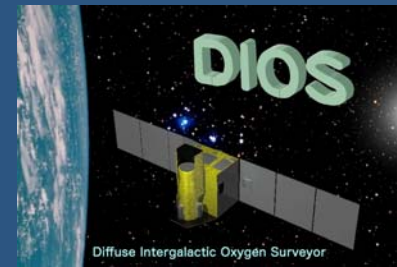
Inclination: 30°

Rotation period: 95 min



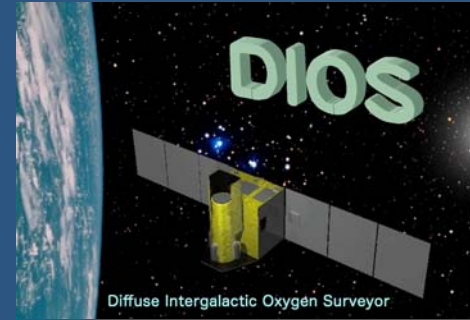
see Ohashi et al. (2004; [astro-ph/0402546](https://arxiv.org/abs/astro-ph/0402546)) for further detail

DIOS: comparison with other missions

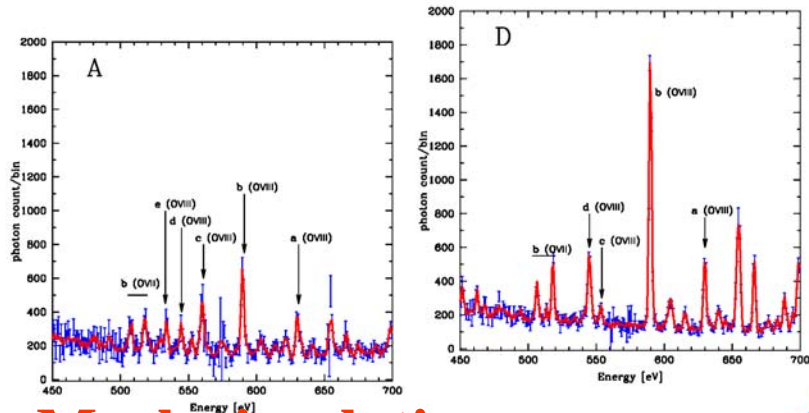


- Very high sensitivity ($S\Omega$ and ΔE) in detecting oxygen emission lines
- Intensity ratios of the lines reveal the temperature and ionization condition of WHIM

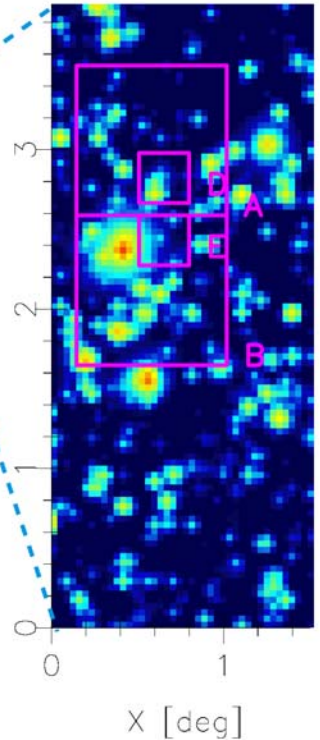
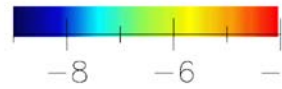
Searching for dark baryons with DIOS (Diffuse Intergalactic Oxygen Surveyor)



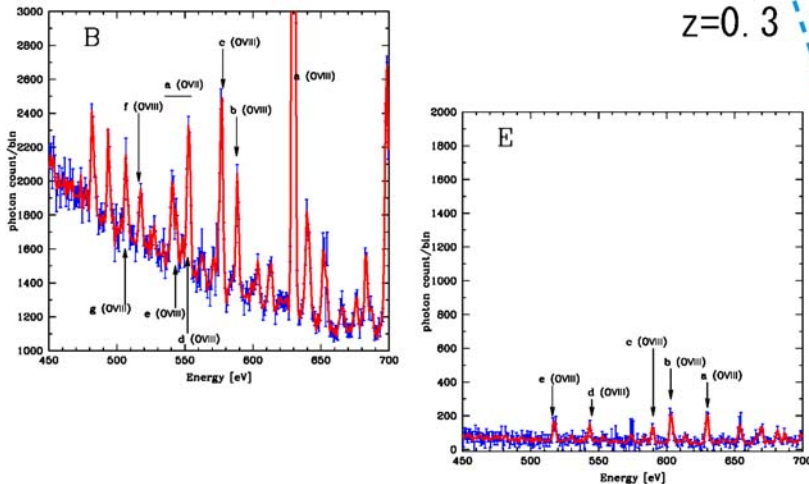
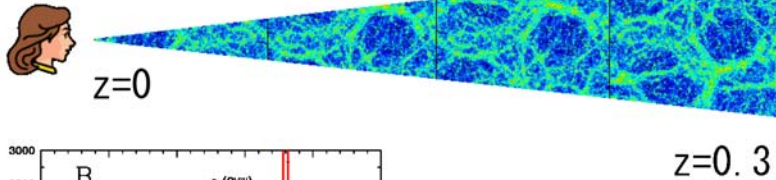
PASJ 55 (2003) 879
astro-ph/0303281



$\text{Log } S_x \text{ [erg/s/cm}^2\text{]}$



Mock simulations



Univ of Tokyo:
K. Yoshikawa

Y. Suto

JAXA/ISAS:

N. Yamasaki

K. Mitsuda

Tokyo Metropolitan Univ.:

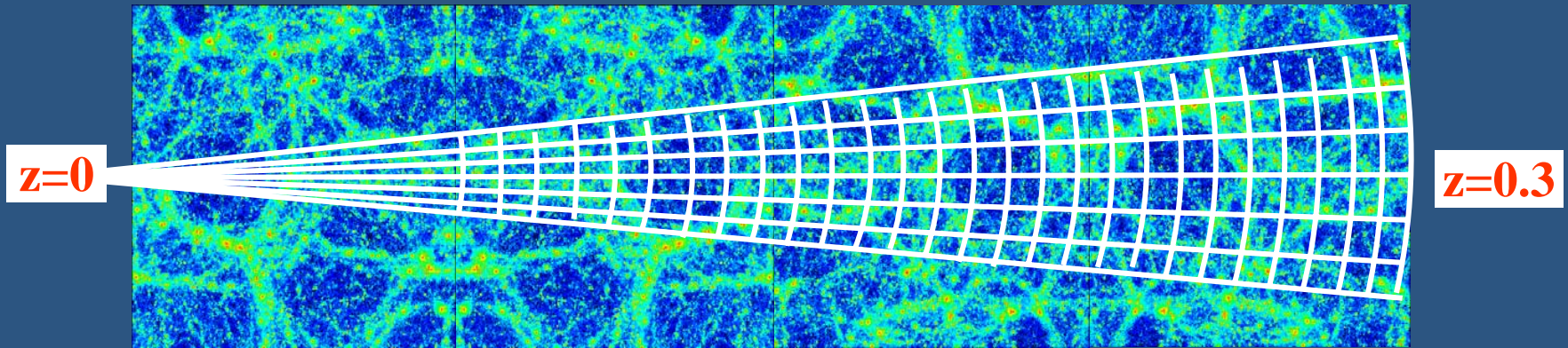
T. Ohashi

Nagoya Univ.:

Y. Tawara

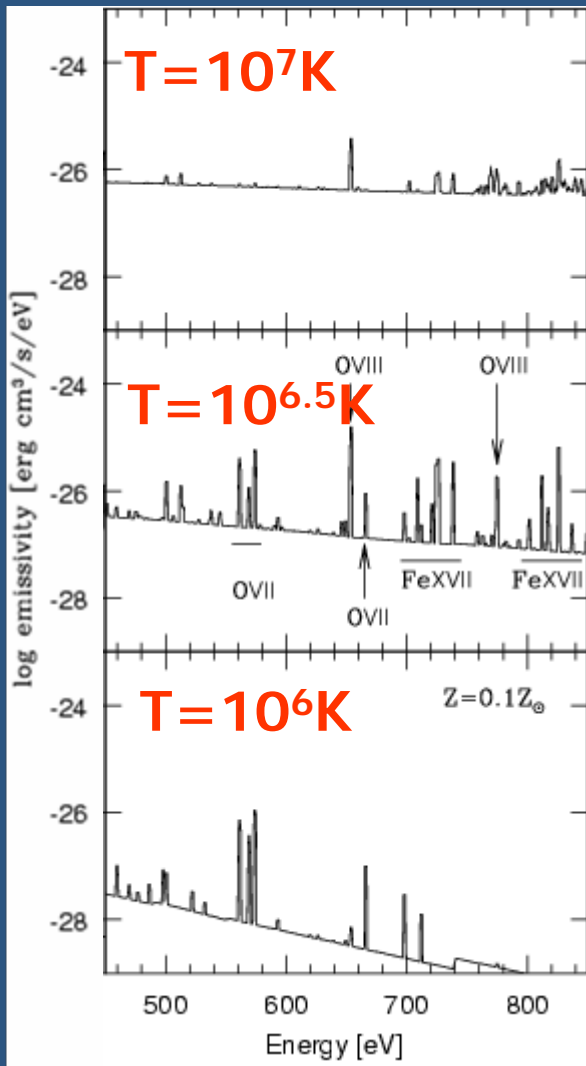
A. Furuzawa

Light-cone output from simulation



- **Cosmological SPH simulation** in $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $\sigma_8=1.0$, and $h=0.7$ CDM with $N=128^3$ each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from $z=0.3$ to $z=0$** by stacking 11 simulation cubes of $(75h^{-1}\text{Mpc})^3$ at different z
- **$5^\circ \times 5^\circ$ FOV mock data** in 64×64 grids on the sky
- 128 bins along the redshift direction ($\Delta z=0.3/128$)

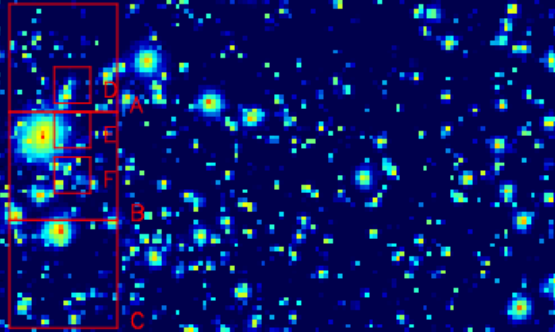
Creating Mock spectra from light-cone simulation output



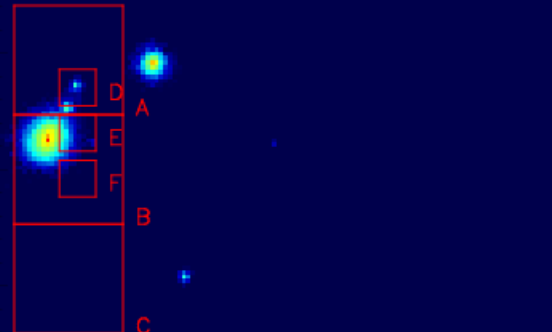
- For a given exposure time,
 - convolve the emissivity according to gas density and temperature in $(5^\circ / 64)^2$ pixels over the lightcone
 - Add the Galactic line emission (McCammon et al. 2002)
 - Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract the Galactic emission and the CXB and obtain the residual spectra for $\Delta E = 2\text{eV}$ resolution.

Surface brightness on the sky

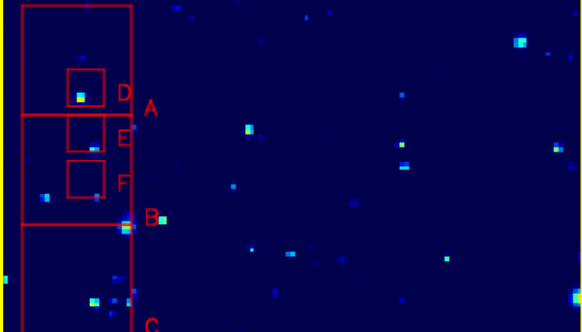
Bolometric X-ray emission



$0.0 < z < 0.3$

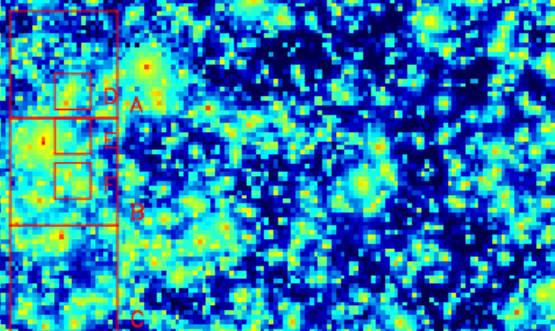


$0.03 < z < 0.04$

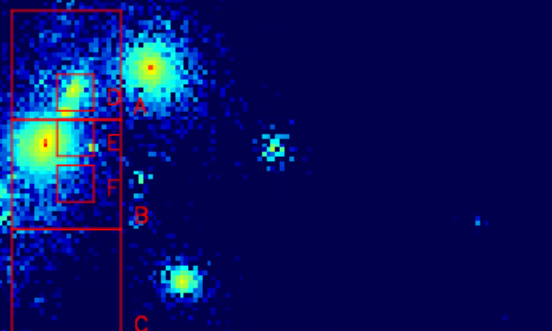


$0.09 < z < 0.11$

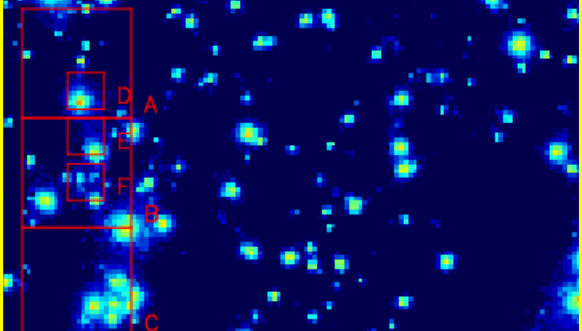
OVII and OVIII line emission



$0.0 < z < 0.3$



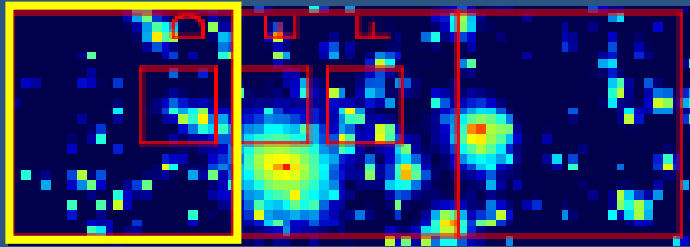
$0.03 < z < 0.04$



$0.09 < z < 0.11$

Simulated spectra: region A

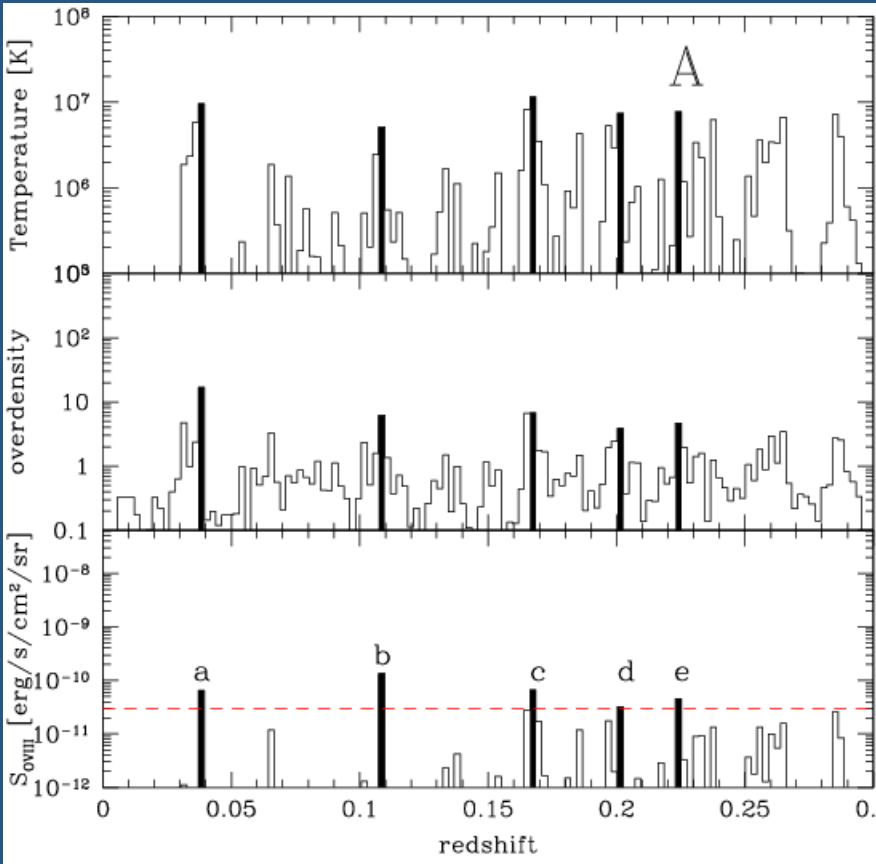
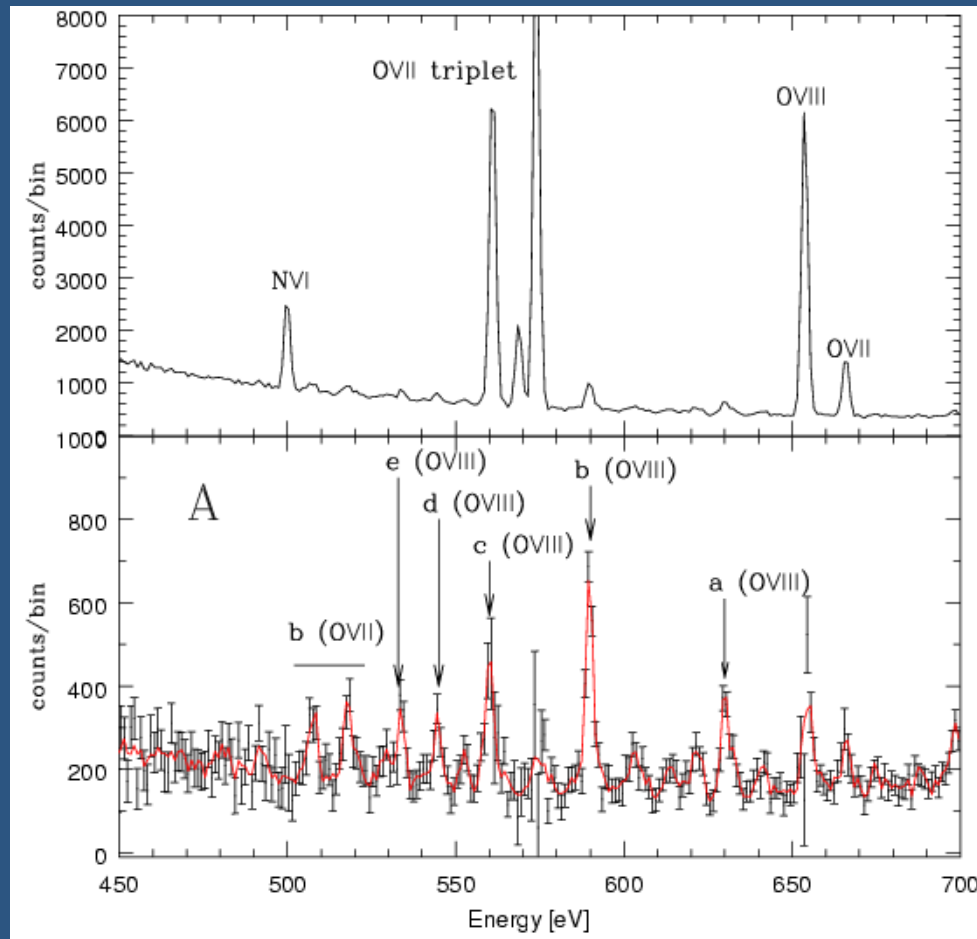
Shallow survey observation with the DIOS field-of-view (16^2 pixels)



A

$$0.94^\circ \times 0.94^\circ = 0.88 \text{ deg}^2$$

$$T_{\text{exposure}} = 3 \times 10^5 \text{ sec}$$



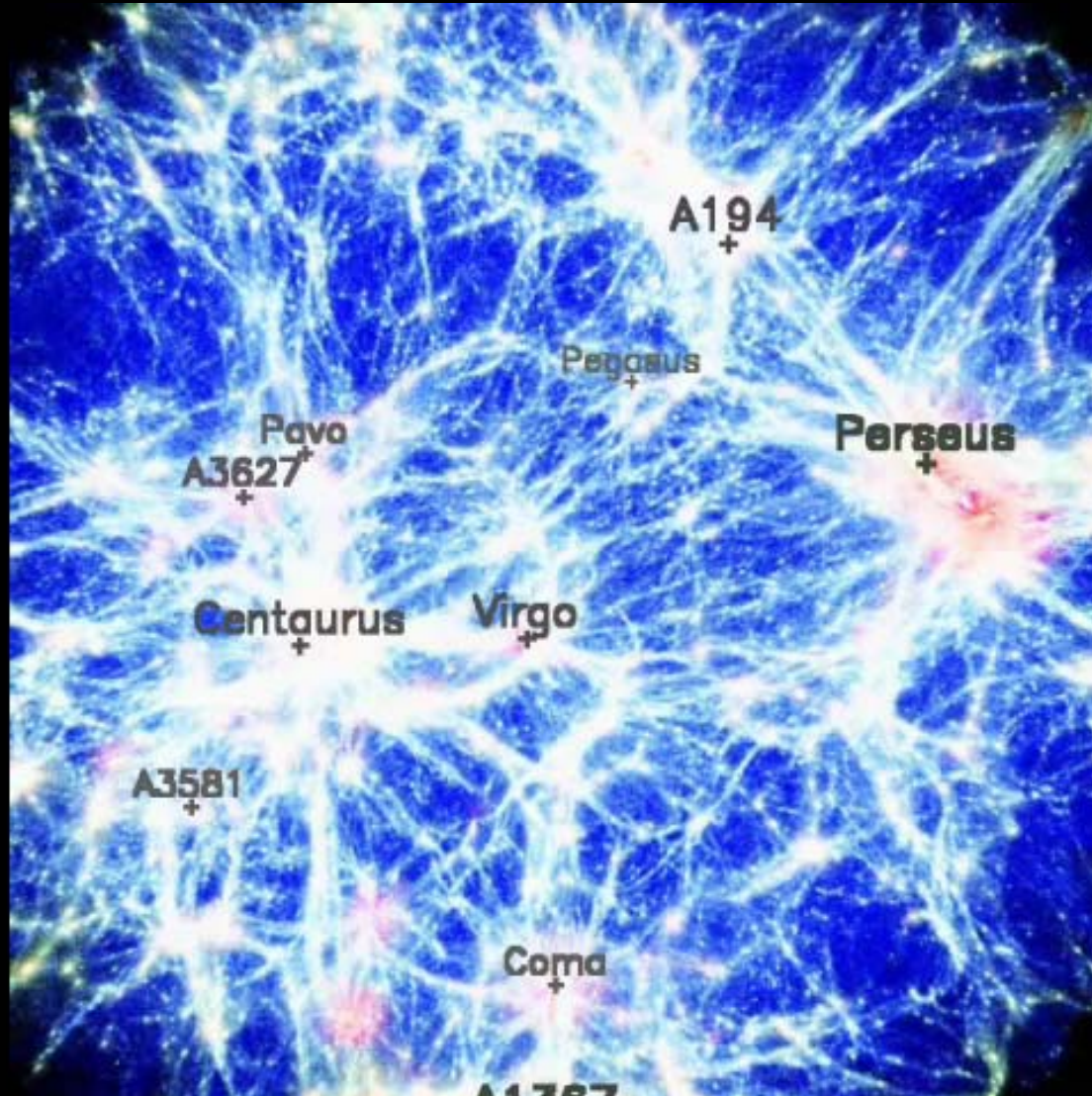
Locating the WHIM in the local universe

Yoshikawa, Dolag, Suto, Sasaki, Yamasaki, Ohashi, Mitsuda, Tawara, Fujimoto, Furusho, Furuzawa, Ishida, Ishisaki & Takei

PASJ 56(2004)939, astro-ph/0408140

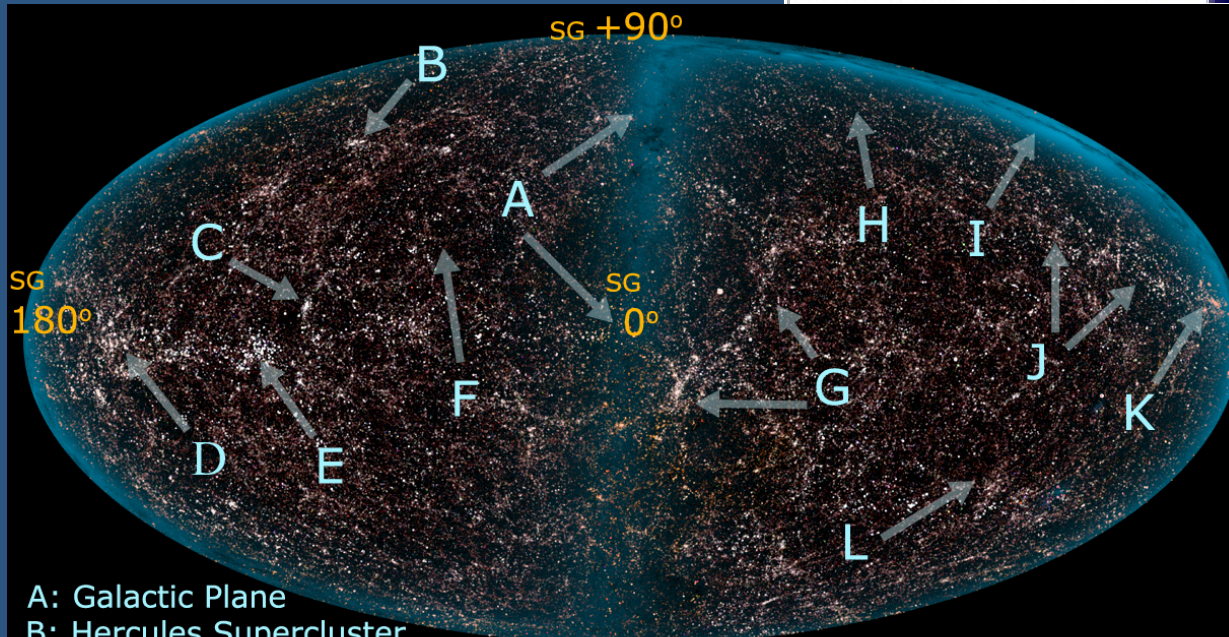
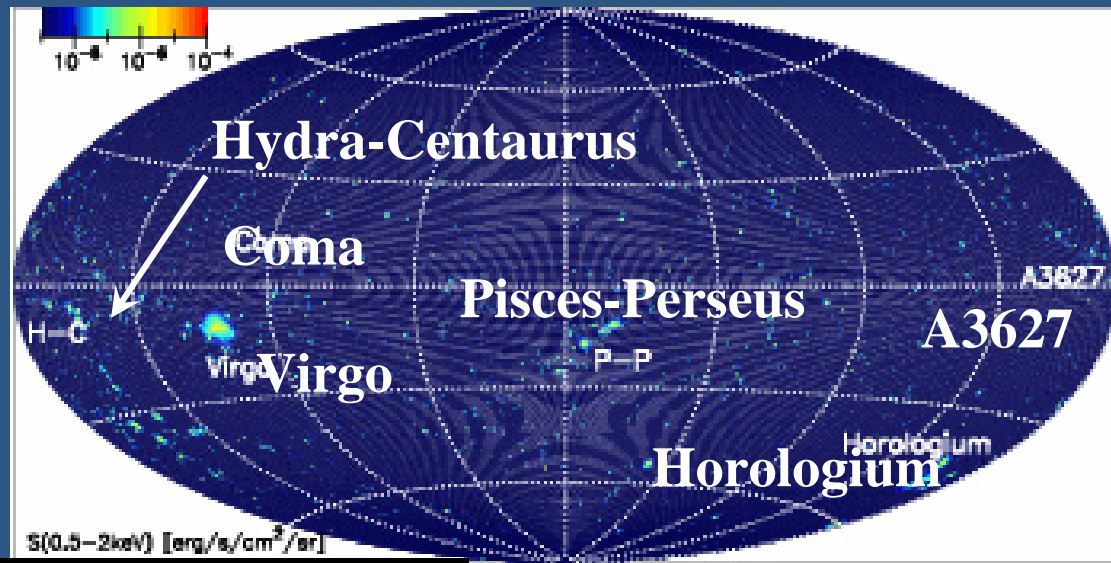
- **Simulation by Dolag et al. (astro-ph/0310902)**
 - Initial condition: smoothing the observed galaxy density field of IRAS 1.2 Jy galaxy survey (over $5h^{-1}\text{Mpc}$), linearly evolving back to $z=50$
 - adiabatic run of dark matter and baryons (without cooling or feedback) in a canonical ΛCDM model
- **Independent and earlier work to consider oxygen emissions from WHIM in constrained simulations**
 - Kravtsov, Klypin & Hoffman, ApJ 571(2002)563

Tour of the simulated local universe



Klaus Dolag (2003)

Simulated local universe vs. 2MASS map

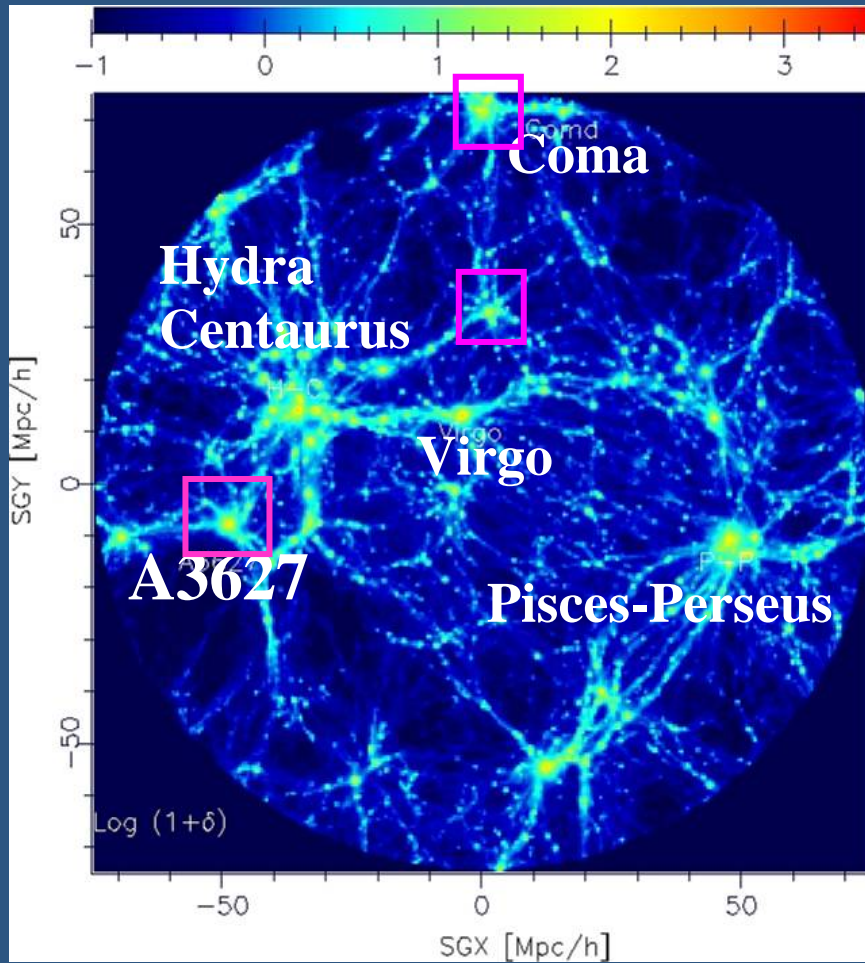


- A: Galactic Plane
- B: Hercules Supercluster
- C: Coma Cluster
- D: Shapley Concentration/
Hydra-Centaurus Supercluster
- E: Virgo Cluster/Local Supercluster
- F: Bootes Void

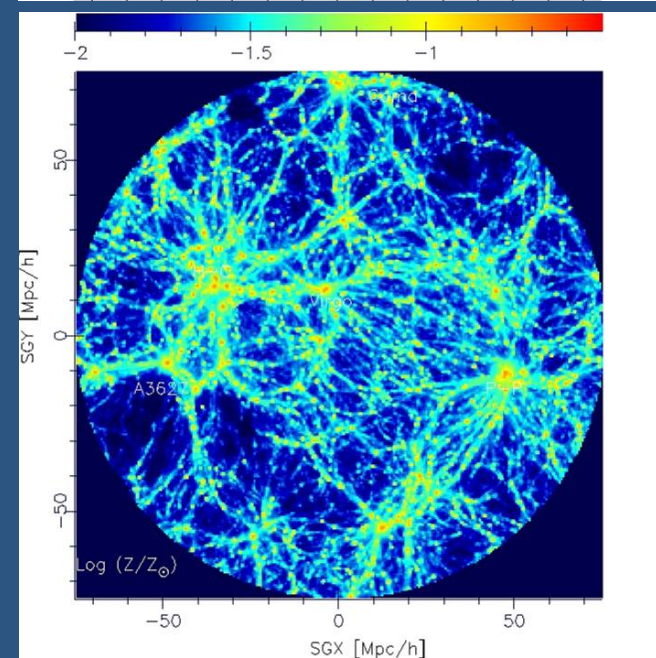
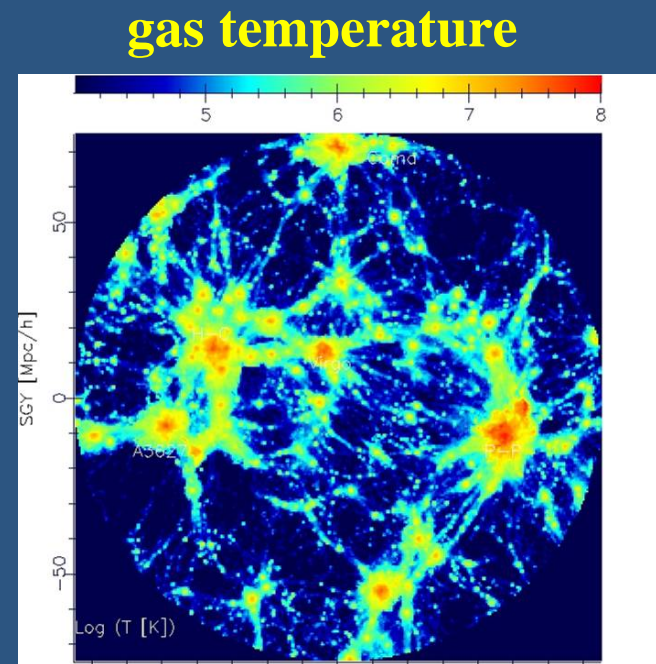
- G: Perseus-Pisces Supercluster
- H: "Local Void"
- I: Galactic Center
- J: Pavo-Indus Supercluster
- K: "Great Attractor"/Abell 3627
- L: Horologium Supercluster

Soft X-ray map of
the simulated
local universe
(Yoshikawa et al.
2004)

Simulated gas distribution on the supergalactic plane



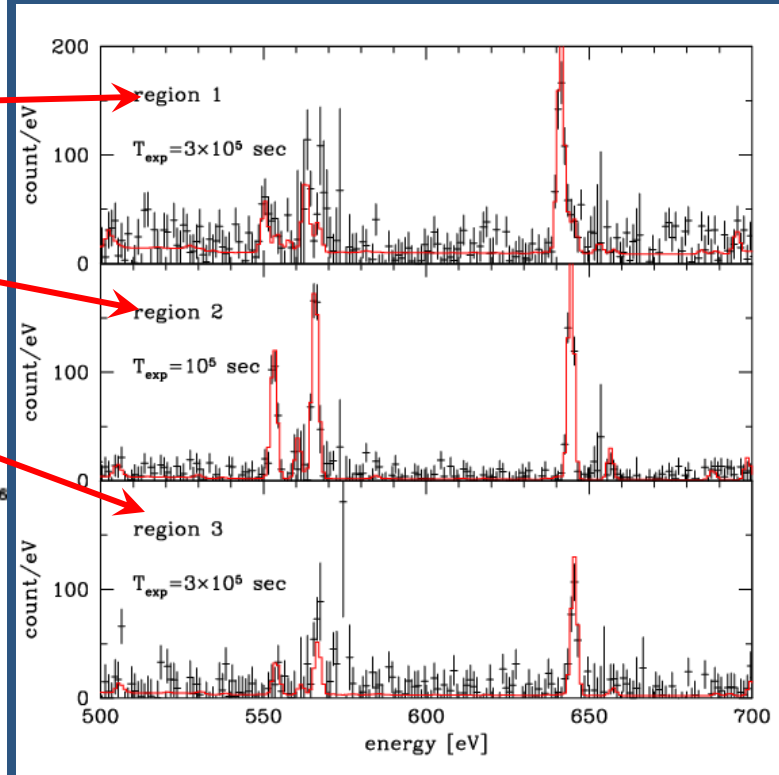
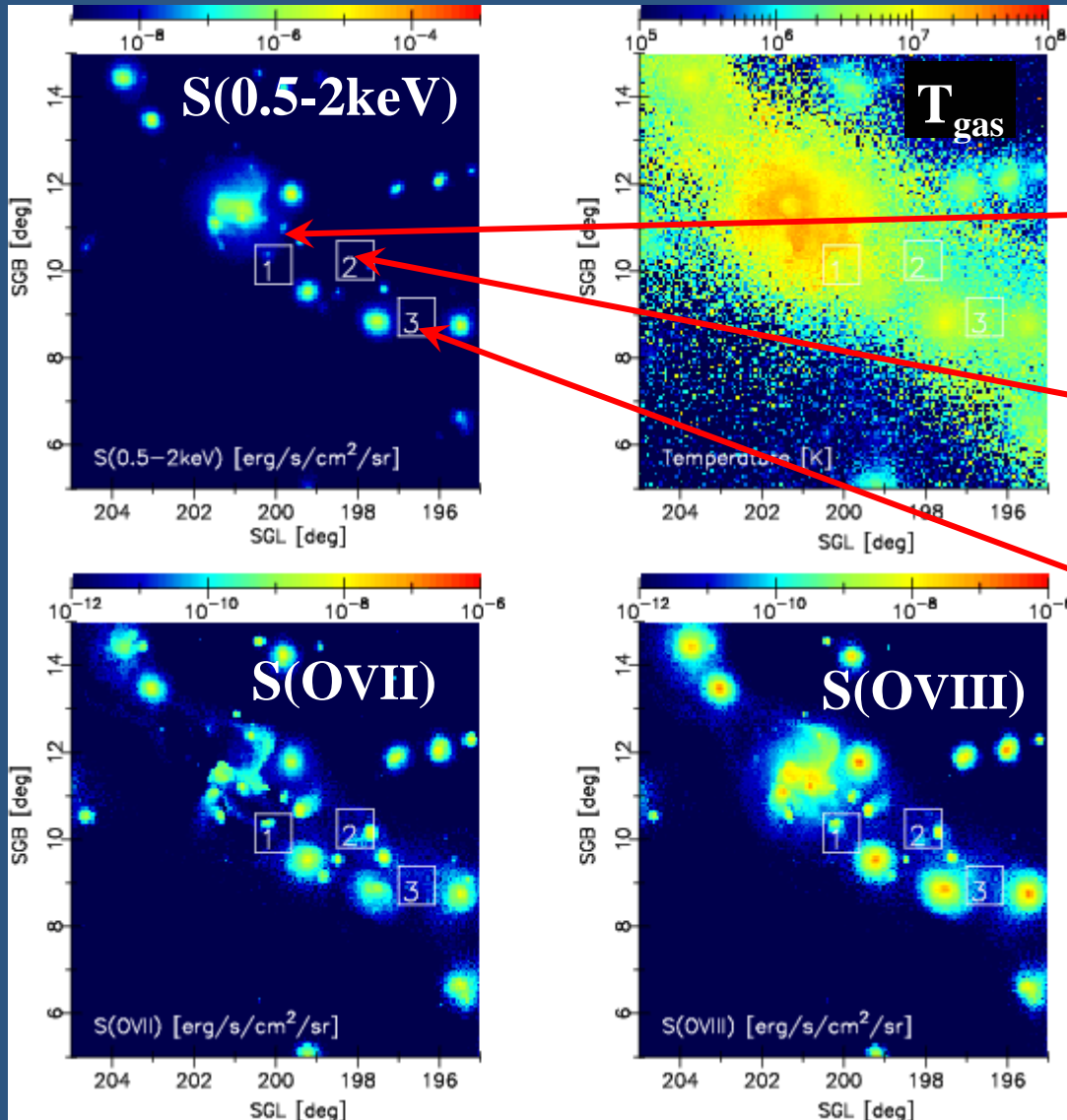
gas density



(adopted) metallicity

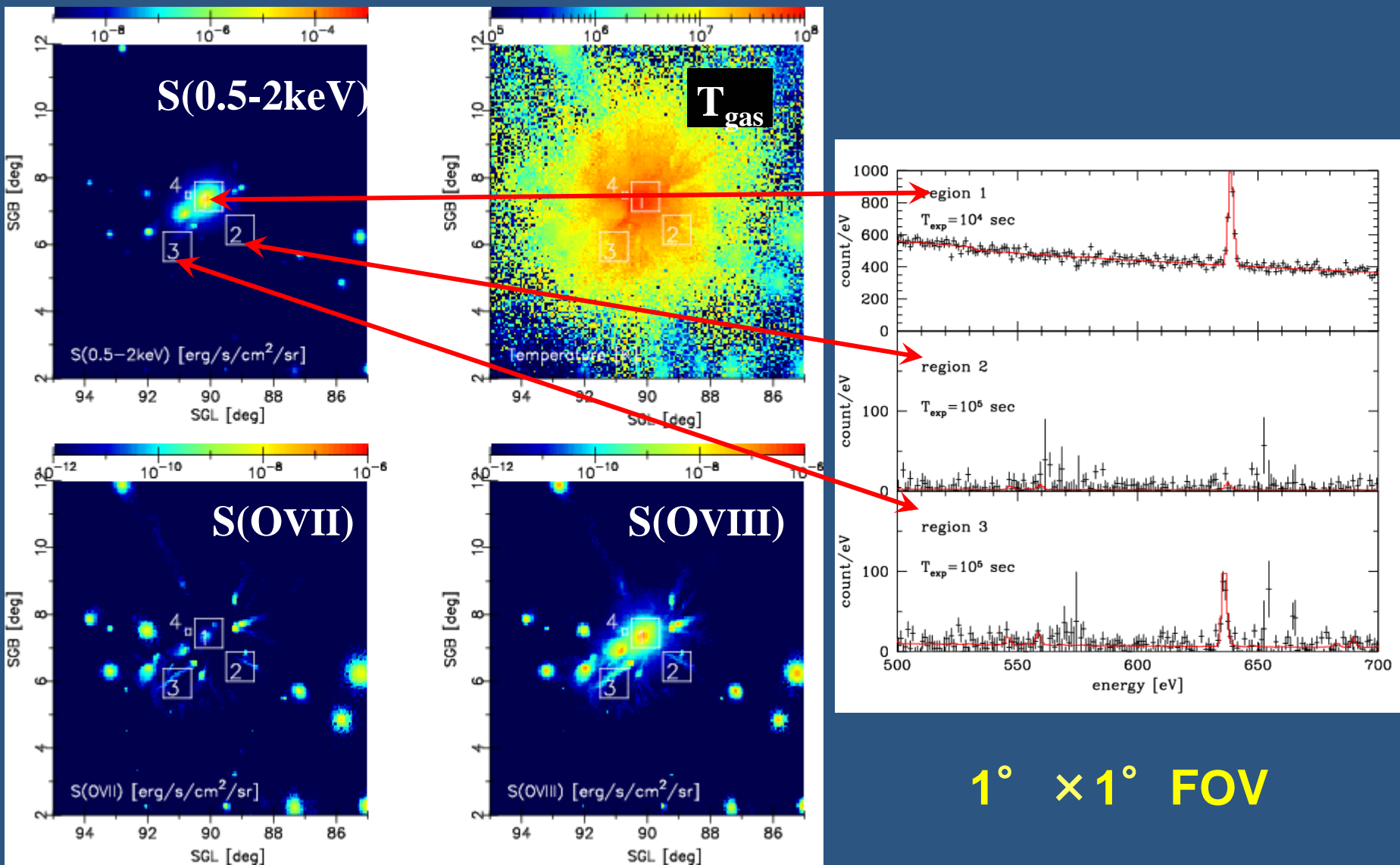
$$Z = 0.02 Z_{\text{solar}} (\rho/\rho_{\text{mean}})^{0.3}$$

Mock observation of X-ray filament extending around simulated A3627



1° × 1° FOV

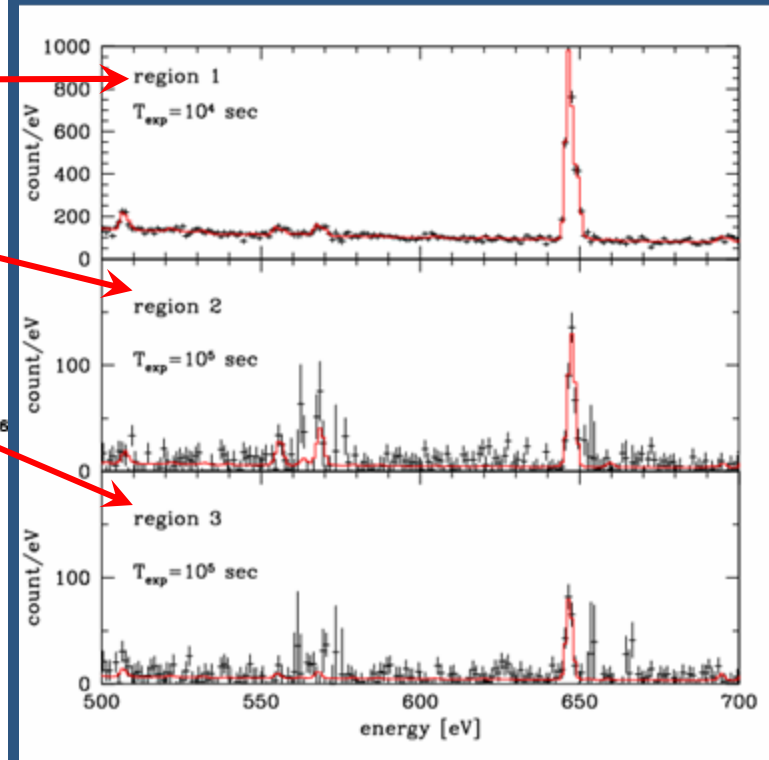
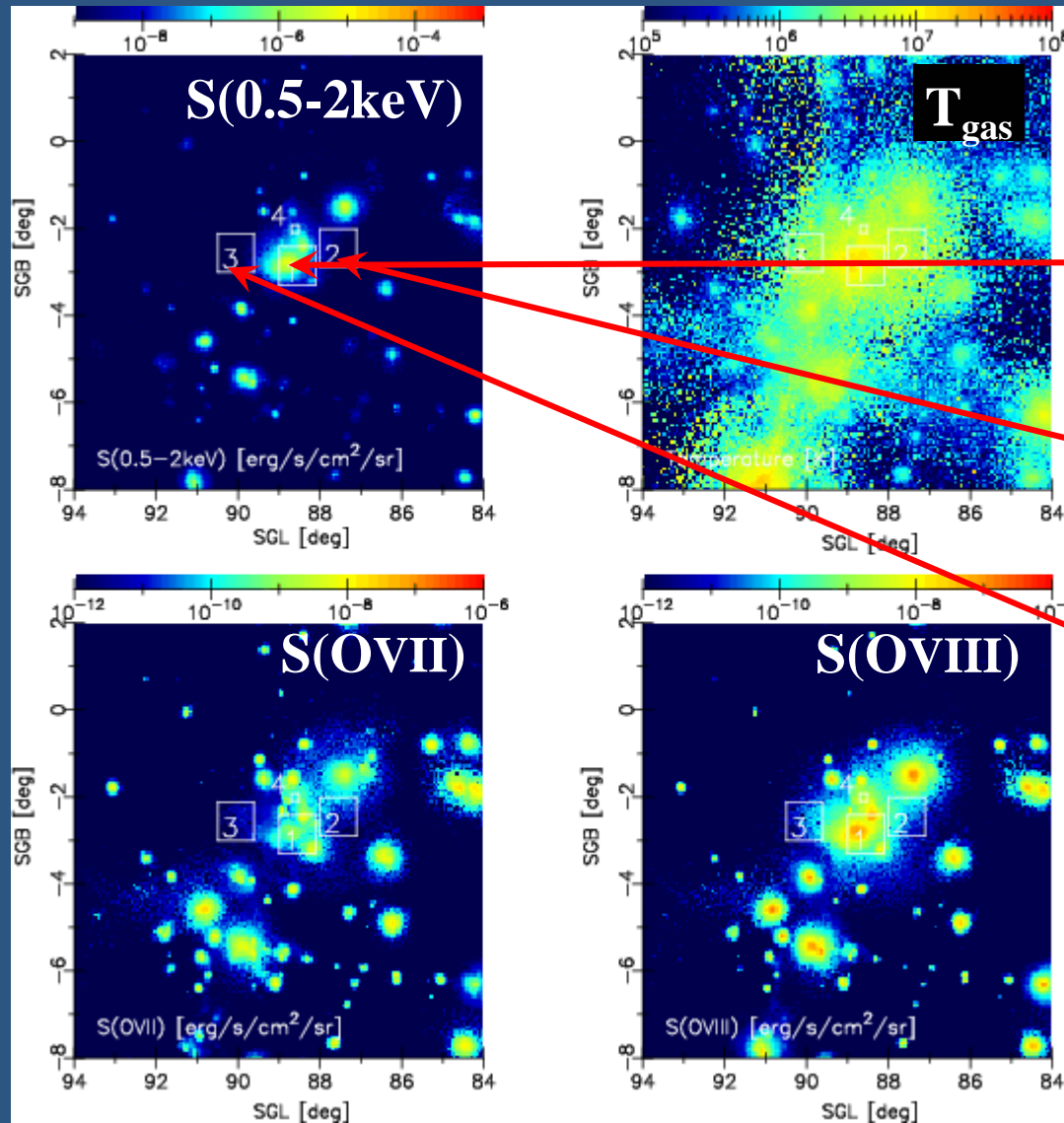
Mock observation of simulated Coma



Surface brightness map [$\text{erg s}^{-1}\text{cm}^{-2}\text{sr}^{-1}$]

a small clump in front of simulated Coma

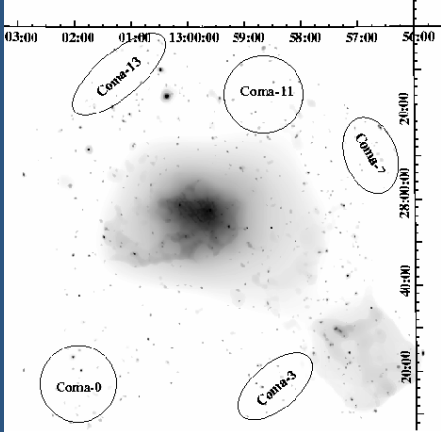
$\sim 10^\circ$ ($\sim 5h^{-1}\text{Mpc}$)
away from the line of
sight toward Coma



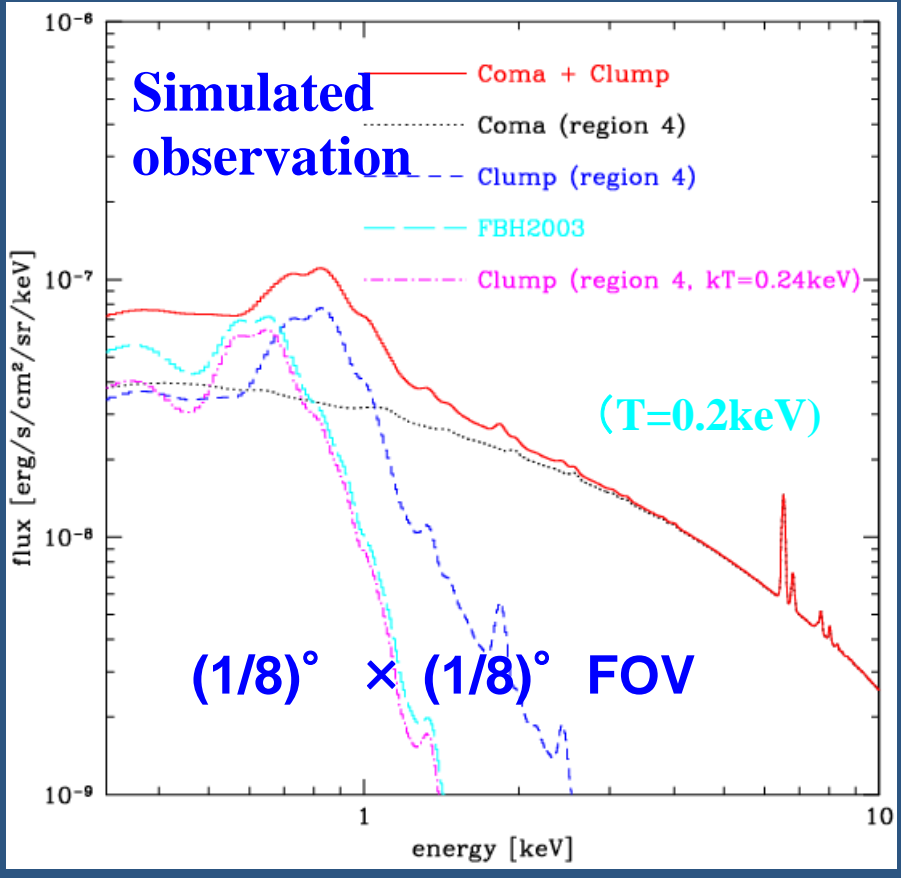
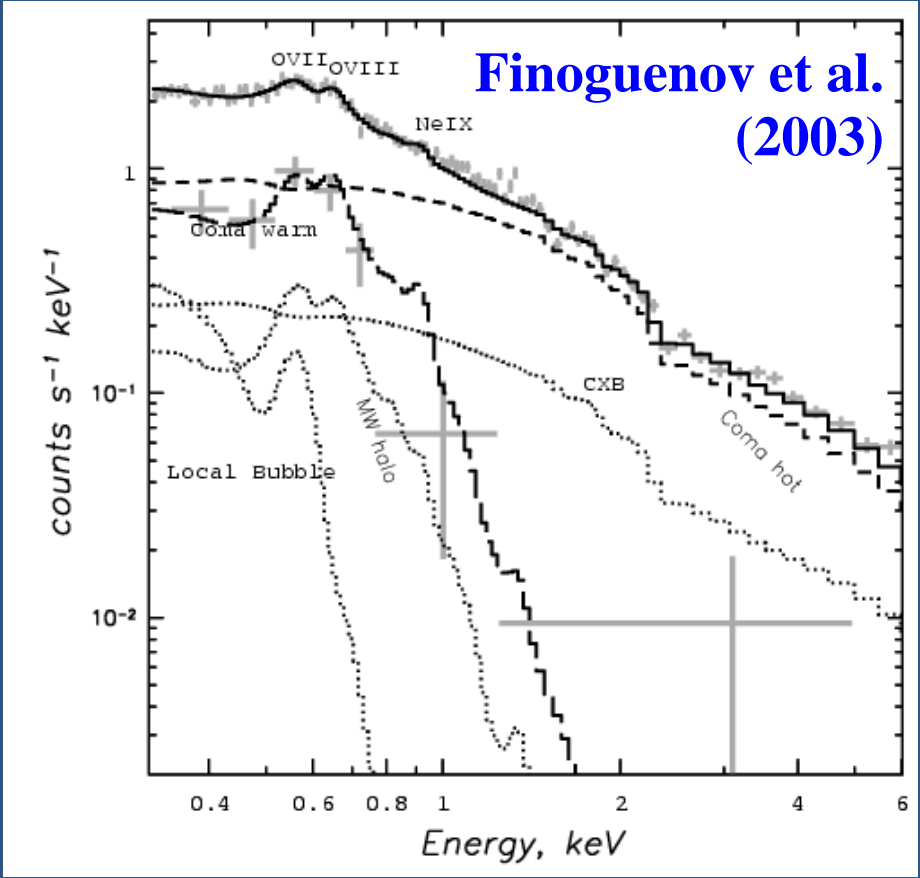
$1^\circ \times 1^\circ$ FOV

Surface brightness map [$\text{erg s}^{-1}\text{cm}^{-2}\text{sr}^{-1}$]

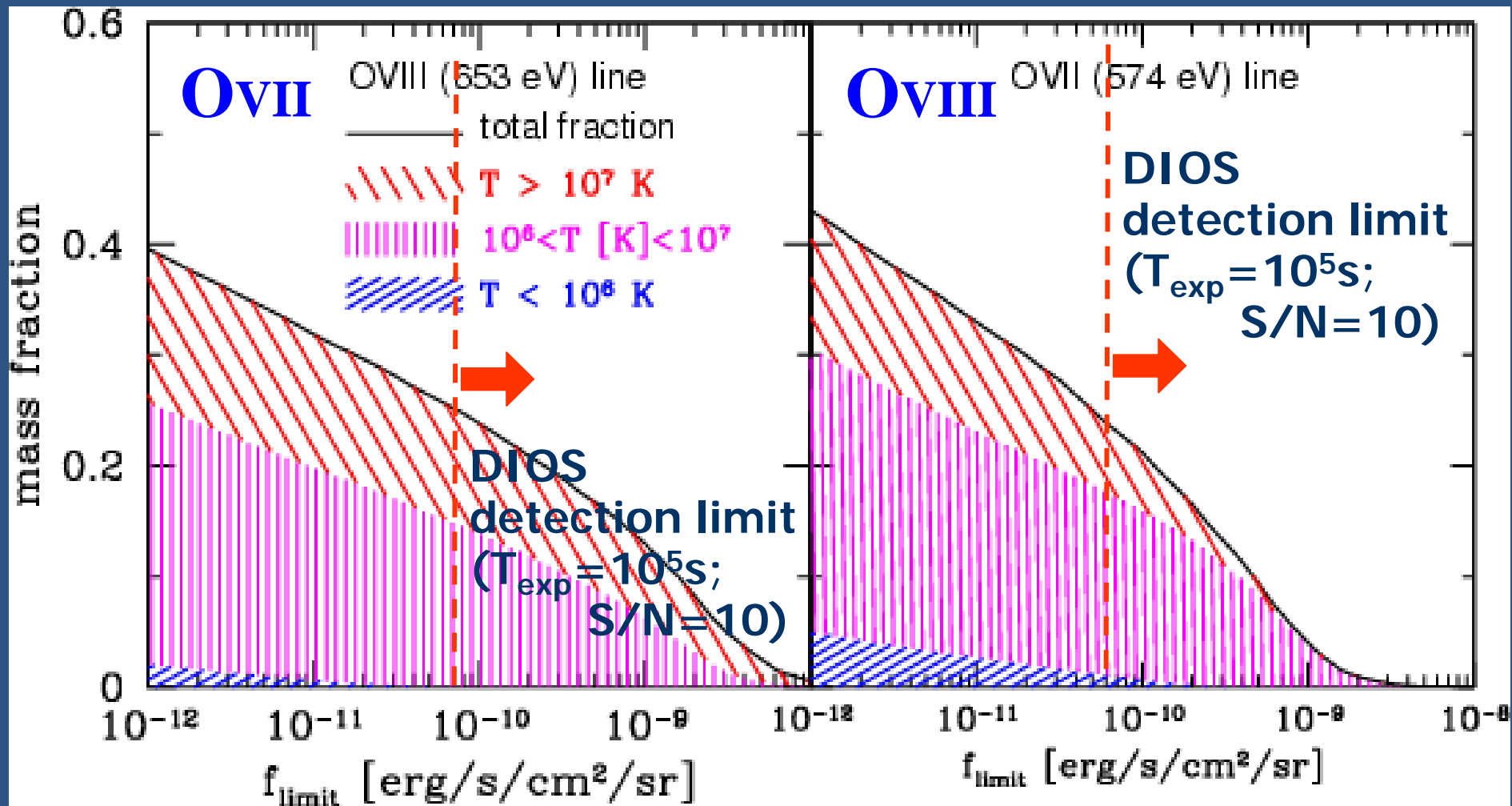
Soft X-ray excess of Coma



- XMM-Newton observations of the outskirts of Coma (Finoguenov, Briel & Henry 2003, A&A 410, 777)
- associated X-ray filament of 0.2keV warm gas ?
- an intervening WHIM clump along the line of sight ?



Fraction of cosmic dark baryons detectable via oxygen emission

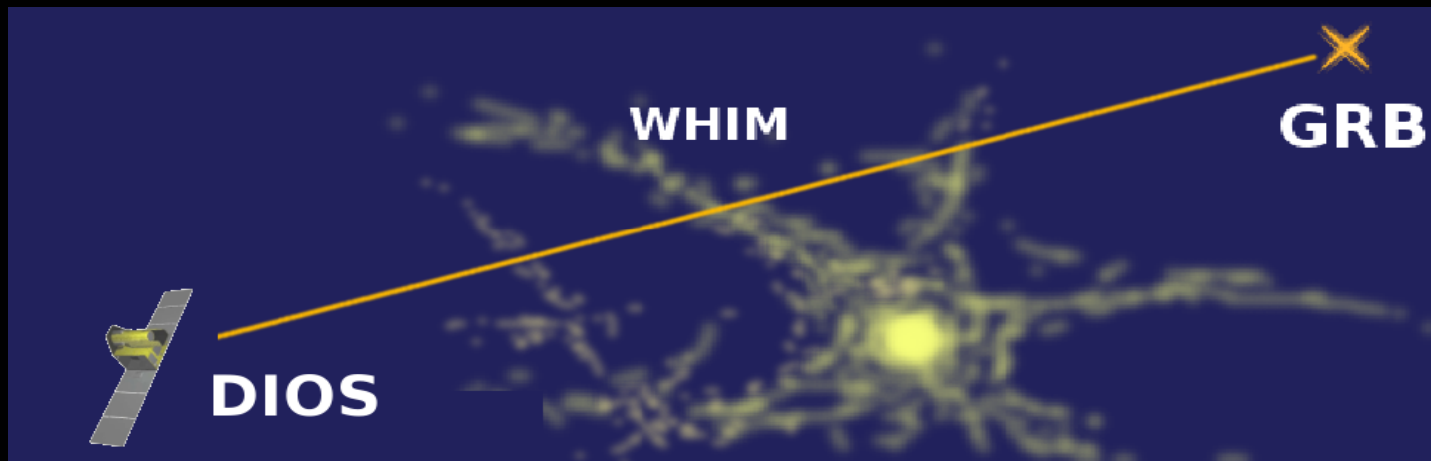


Searching for dark baryons via absorption line systems in a Gamma-ray burst afterglow

H.Kawahara, K.Yoshikawa, S.Sasaki, Y.Suto, N.Kawai, T.Ohashi, N.Yamasaki & K.Mitsuda

astro-ph/0504594 (submitted to Pub.Astron.Soc.Japan 2005)

- first proposed by Fiore et al. (2000)
- can probe higher z
- can search for emission line counterparts later



Model for GRB afterglow

- Average spectrum fitted by Piro (2004)

$$F_{\text{GRB}}(t, E) = F_0 \left(\frac{t}{40 \text{ k sec}} \right)^{-1.2} \left(\frac{E}{1 \text{ keV}} \right)^{-1.13} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ keV}^{-1}$$

- Frequency of GRB afterglow with

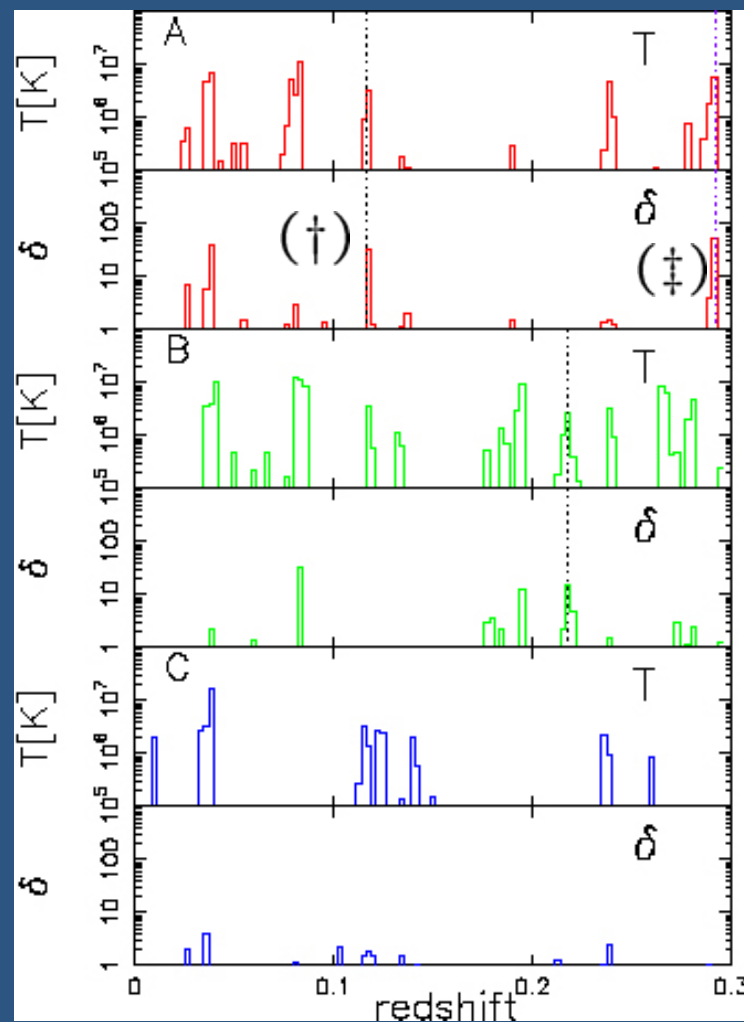
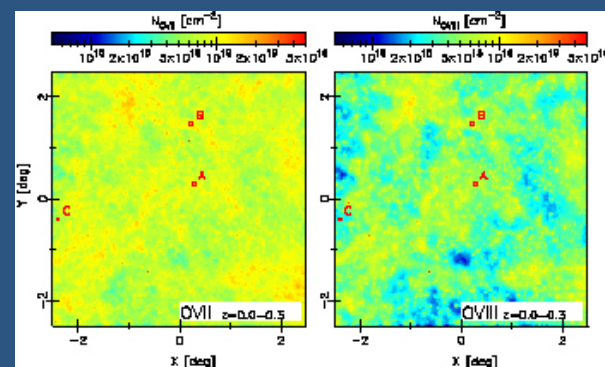
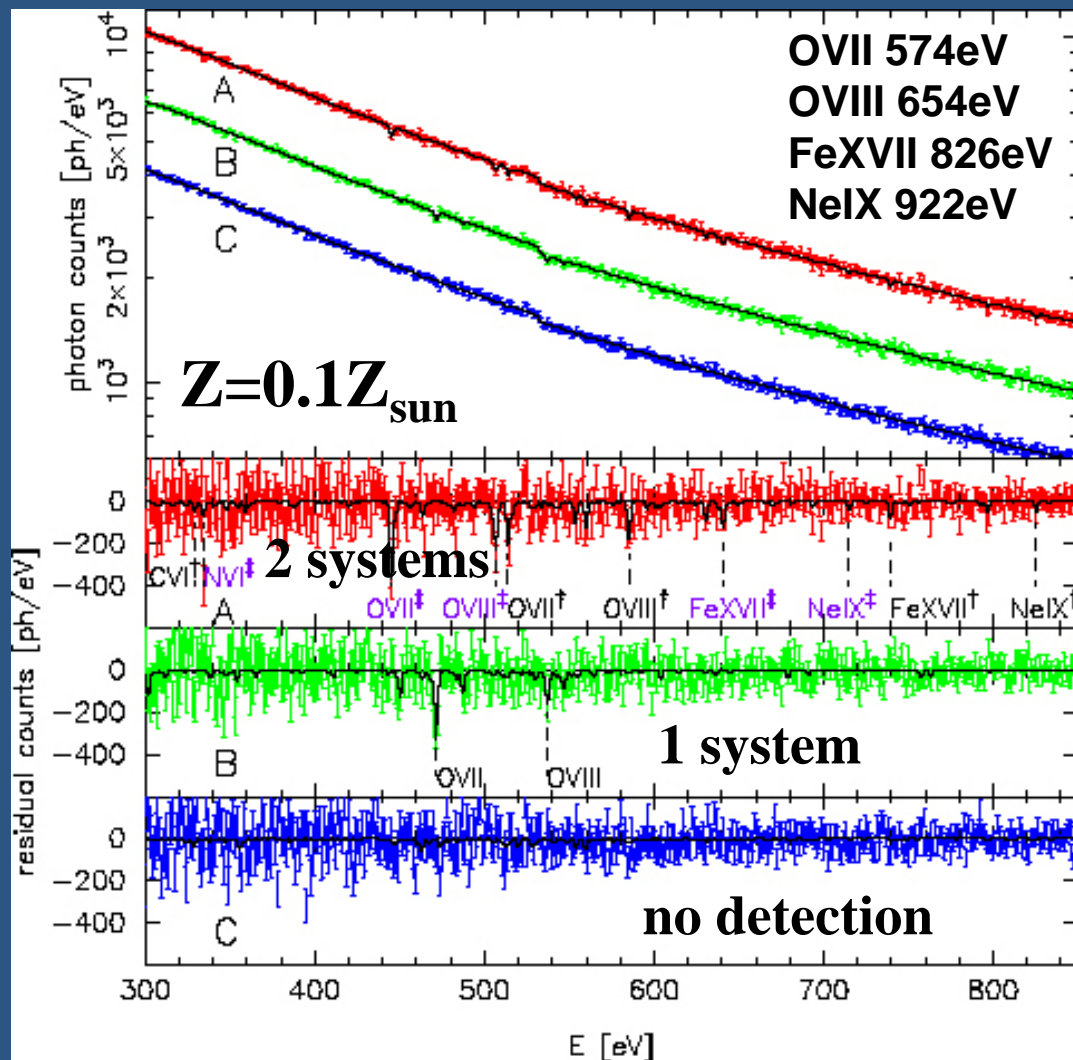
$$F > F_0 = 6 \times 10^{-11} \text{ erg/s/cm}^2/\text{keV}$$

→ ~40/year/sky (from 6 years' BeppoSAX data)

- observing strategy: start of the observation and exposure time for 5000 photons/eV@500eV with XEUS (impossible with DIOS...)

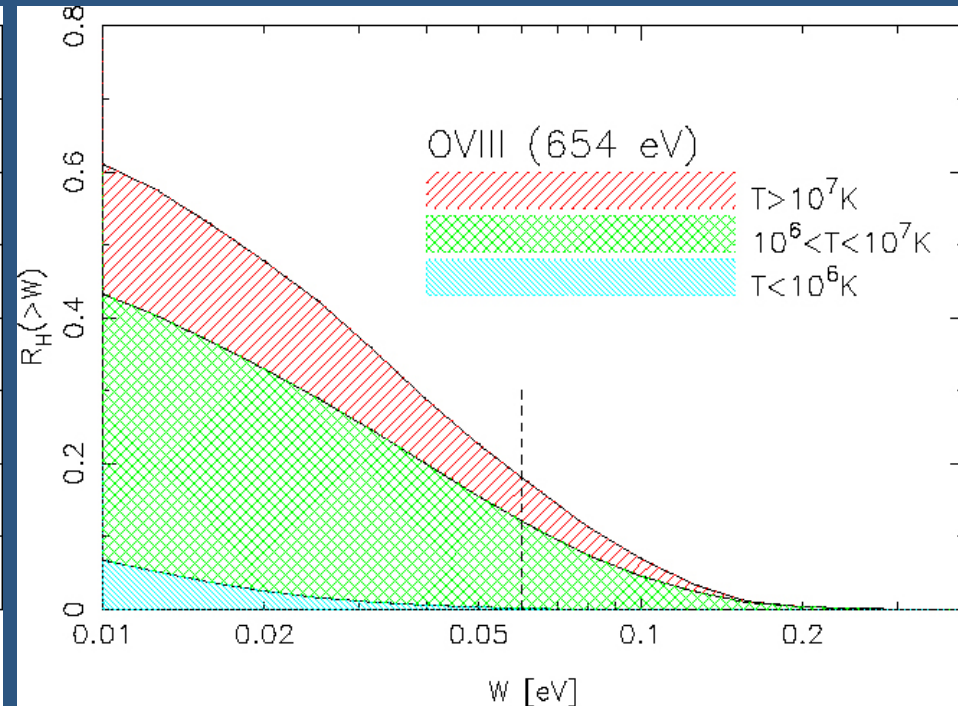
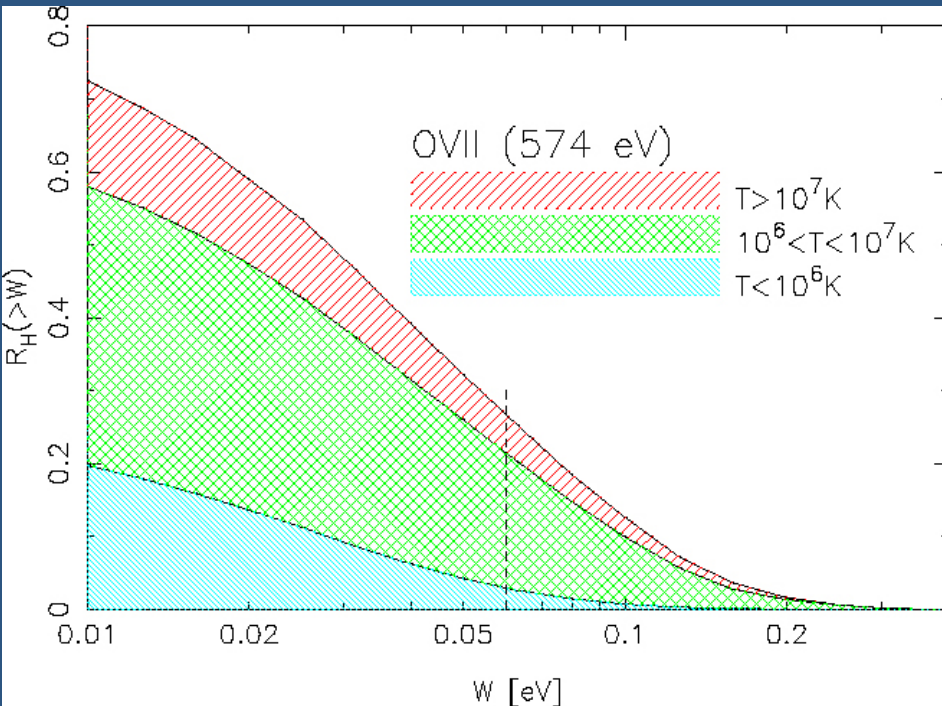
- $t_i = 1 \text{ hour}$ and $t_{\text{exp}} = 5 \text{ ksec}$ (for F_0)
- $t_i = 2 \text{ hour}$ and $t_{\text{exp}} = 12 \text{ ksec}$ (for F_0)
- $t_i = 1 \text{ day}$ and $t_{\text{exp}} = 15 \text{ ksec}$ (for $10F_0$)

Mock transmission spectra of a GRB afterglow



Kawahara et al. (2005)

baryon fraction detectable by absorption lines in the GRB afterglow

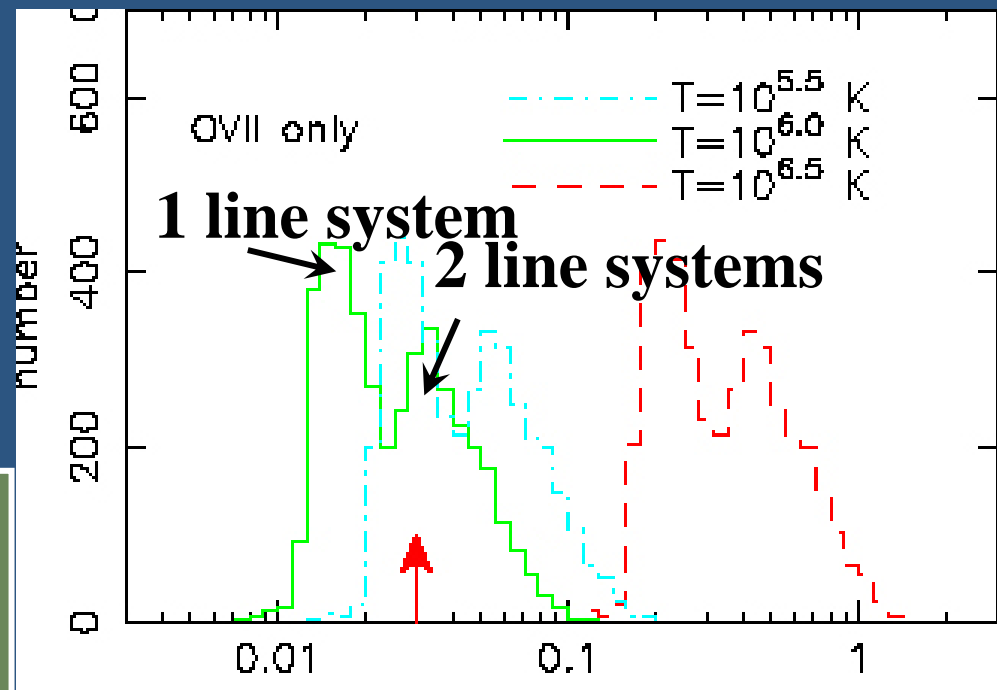


W: equivalent width
 $R_H(>W)$: cumulative gas mass fraction

$$R_H(>W) = \frac{\sum_{i=1}^{6400} N_{H,i}^{sim}(>W)}{\sum_{i=1}^{6400} N_{H,i}^{sim}(>0)}$$

Baryon density from oxygen absorption line systems in the GRB afterglow

e.g.,
 $\Omega_b^{WHIM} = (2.7^{+3.8\%}_{-1.9\%}) \times 10^{-[O/H]_{-1}}$
 (along Mkn421 if $T=10^{6.1}K$;
 Nicastro et al. 2005)



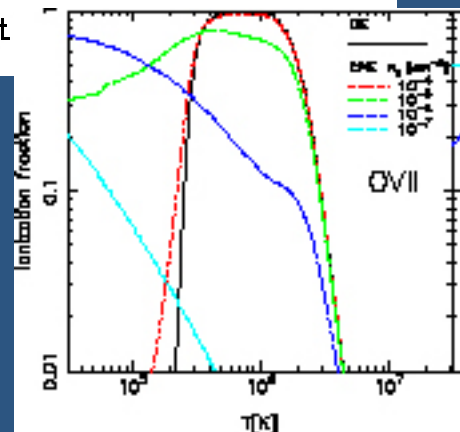
fraction of gas in baryons

$$\Omega_b^{est} = \frac{\Omega_{gas}^{WHIM,est}(>W)}{R_H(>W)} \cdot \frac{1}{f_{gas}} \cdot \left\langle \frac{N_H^{sim}(>W)}{N_H^{est}(>W)} \right\rangle$$

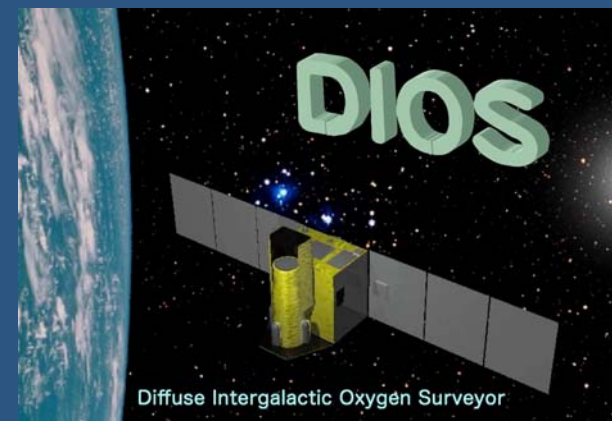
undetected
gas fraction

underestimate bias due to
the clumpiness of WHIM

\Rightarrow very sensitive to the assumed temperature and metallicity



Prospects for dark baryon search via WHIM spectroscopy



- **DIOS** will detect dark baryons in the form of WHIM from oxygen emission line survey (Yoshikawa et al. 2003)
 - $\Delta E = 2\text{eV}$, $S_{\text{eff}} \Omega = 100 [\text{cm}^2 \text{deg}^2]$, $T_{\text{exp}} = 10^5\text{s}$, $S/N = 10$
 - flux limit = $6 \times 10^{-11} [\text{erg/s/cm}^2/\text{sr}]$
- **DIOS** will detect WHIM at outskirts of known galaxy clusters in the local universe (Yoshikawa et al. 2004)
 - origin of soft X-ray excess reported for clusters (e.g., Coma)
- **XEUS** will identify ~ 1 OVII absorption line system along a bright GRB (40 per year) with $> 3\sigma$ (Kawahara et al. 2005)
 - interesting but statistics is inevitably limited
 - estimate of baryon density is subject to big uncertainties such as temperature and metallicity ...